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Using Spectral Vegetation Indices to Study the Growth of *Opuntia ficus-indica* and Identify Suitable Production Sites in the Southwestern Region of Saudi Arabia

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ABSTRACT

This study was conducted to investigate the growth of two *Opuntia ficus-indica* varieties (var. *inermis* and var. *Mill*) in eleven geographical sites in the southwestern region of Saudi Arabia. Selected spectral vegetation indices (VIs) were used to identify suitable production sites for each variety. The results showed significant variations between the studied sites for both varieties. The best growth performance of the *inermis* variety was at Thaqeef Canal site, as evidenced by the highest values of the Normalised Difference Water Index (NDWI, 0.477), Normalised Difference Vegetation Index (NDVI, 0.553) and the Green Normalised Difference Vegetation Index (GNDVI, 0.392), and the second highest value of the Soil Adjusted Vegetation Index (SAV, 0.392) compared to other sites. While the moderate growth performance of the var. *Mill* was at the Bani Saad site compared to other sites, as indicated by the values of NDVI (0.575), SAVI (0.428), and GNDVI (0.408). A land suitability analysis focusing on site-variety interactions was conducted using the Analytical Hierarchy Process (AHP). The results indicated that Thaqeef Canal and Al-Shifa were the most suitable sites for the growth of both

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Opuntia ficus-indica varieties. Other sites considered highly suitable for growing the variety *inermis* include Al-hada, Wadi Muharrm and Sayyadah. While Baqran Village, Al-Thumalah farm, and Al-Thumalah were considered highly suitable for growing the variety of *Mill*. The results of this study provide a good basis for future studies aimed at improving agricultural practices and decision-making related to the production of *Opuntia ficus-indica* in the southwestern region of Saudi Arabia.

Keywords: Arid regions, cactus plants, land suitability, spectral reflectance, vegetation indices

INTRODUCTION

Saudi Arabia is characterised by its arid environment and limited water resources, with about 80-90% of the water supply coming from groundwater, which is rapidly depleting and requires proper management (Al-Salamah et al., 2011). As these conditions have exacerbated the problem of desertification and increased sand encroachment on agricultural lands, many challenges have arisen that have led to a shift in plant species in terms of their presence or absence in habitats. The southwestern region of Saudi Arabia encompasses a wide and diverse range of plant species and populations across various ecological niches. Productivity in this region can be enhanced by growing adaptable crops such as prickly pear, an excellent plant for soil conservation and regeneration in arid and semi-arid environments (Al-Aklabi et al., 2016; Osman et al., 2024).

Cactus crops are gaining increasing interest worldwide. In particular, cactus pear (*Opuntia ficus-indica*) can grow on lands where other crops fail due to its unique properties, which provide the ability to withstand harsh conditions, and thus can be used to restore degraded lands (Kumar et al., 2018). Cactus pear has proven its potential as a versatile and sustainable crop in arid and semi-arid regions due to its high-water use efficiency and tolerance to dry conditions (Slot & Fort, 2024). Also, Shoukat et al. (2023) reported that cactus pear is highly valued worldwide for its effective uses in medicine, cosmetics, human nutrition, livestock feed, wastewater treatment, fuel production, and sustainable and environmentally friendly building materials, in addition to its versatility and high environmental adaptability. The phenological, physiological, and structural adaptations enable *Opuntia ficus indica* to maintain reasonable productivity levels in dry rangeland conditions and even under extreme water scarcity (Hassa et al., 2020). In addition, Naorem et al. (2024) noted that the ability of cactus pear to grow in arid environments and poor soils makes it ideal for combating desertification and soil erosion, and it can also be used as livestock feed. Furthermore, its nutritional properties, including antioxidant and antidiabetic effects, enhance its value as a food source. The same has been stated by Sipango et al. (2022) that due to its adaptability to harsh conditions of less fertile soils, high temperatures, and low rainfall, the prickly pear cactus is drought-resistant and well adapted to high temperatures in arid regions, especially on low-profile soils.

Remote sensing plays an important role in the fields of landscape ecology and ecosystem monitoring because it relies on aggregate scales as well as the powerful panoramic view of its spatial and temporal images (Mucher & Hazeu, 2021). In addition, Matyukira and Mhangara (2024) noted that the ability of remote sensing technologies to provide detailed vegetation maps is vital for environmental management and monitoring, where these technologies enable assessment of vegetation status and temporal and spatial changes, providing deep insights into ecosystem dynamics. Nizamani et al. (2024) also noted that GIS and remote sensing technologies have become essential tools for assessing ecosystem services and conserving biodiversity, as they provide valuable spatial and temporal data that enable scientists and decision-makers to monitor and make effective decisions about environmental processes, threats, and conservation strategies. In this context, vegetation indices, derived from remote sensing-based plant canopy data through mathematical algorithms, are simple and highly effective for quantitative and qualitative assessments of vegetation cover, plant vigour, and growth dynamics (Xue & Su, 2017). Therefore, this study aimed to highlight the importance of analysing the growth performance of two *Opuntia ficus-indica* varieties and to identify the appropriate production sites using spectral vegetation indices. More specifically, the study aimed to explore which variety performs best in a given location.

MATERIALS AND METHODS

The Study Area

This study was conducted in the southwestern area of Saudi Arabia, which is considered an important bioclimatic zone for the growth of *Opuntia ficus-indica*. It covers eleven geographical sites (Table 1) in Al-Taif and Maysan Governorates (Al-Ahada, Al-Hadab, Al-Thumalah Farm, Al-Shafa, Bani Saad, Baqran Village, Jabajib, Sayadah, Thaqeef Canal, Al-Thumalah, and Wadi Muharrm), as shown in Figure 1. The southwestern region of Saudi Arabia is characterised by sandy plains, rocky outcrops, valleys, and fallow lands. This region includes a wide range of plant species in a diverse ecological site.

Sampling Strategy

A total of 11 study sites were identified in the southwestern region (Al-Taif and Mayson) of Saudi Arabia using ArcGIS tools “Create Spatial Sampling Locations”. The stratified random sampling method was adopted, and the elevation map was used as the input for the stratum (Figure 1). A 5 km x 5 km grid was generated and considered the main plot in the sampled villages/farms (Table 1). For ground truth data and spectral reflectance measurements, subsequently, the main plots were divided into composite plots (1 km x 1 km). A total of 54 composite plots were then identified and further subdivided into (30 m x 30 m) plots to conduct the study on each composite plot across all study sites (Figure 2). The subplots were further subdivided into smaller subplots (3m x 3m) where the opuntia species were enumerated, and the cladodes were collected for spectral reflectance measurements. A bottom-up approach was adopted in processing the spectral data for land suitability analysis, whereby the unit plot data were upscaled into subplots and composite plots.

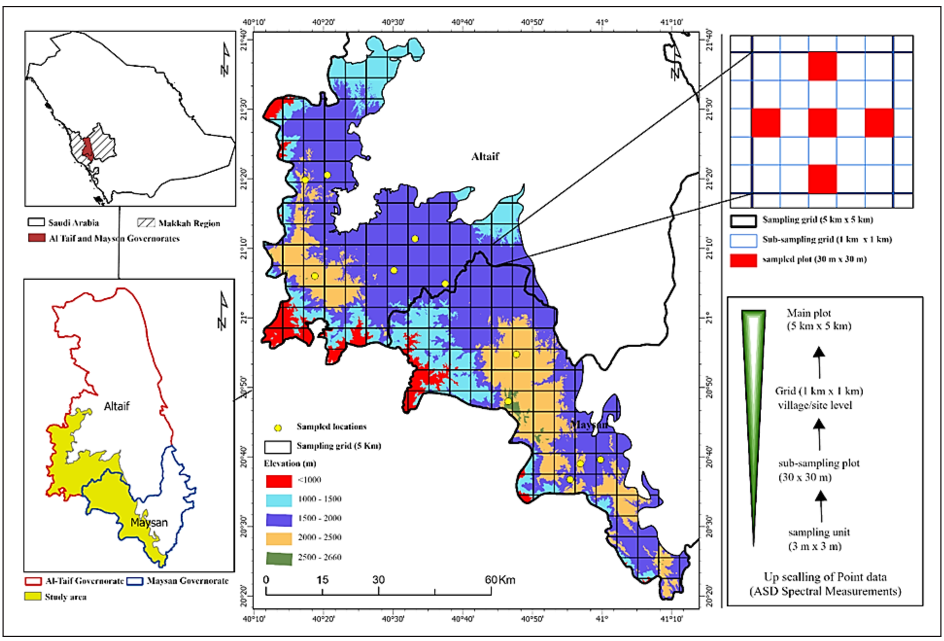

Figure 1. Location map of the study sites

Table 1
*Coordinates of the study sites assigned codes and sampling strategy for cladode collection and spectral data measurements; *no presence of Opuntia ficus-indica (L) Mill*

Study site		Longitude	Latitude	Main Plot (5 km x 5 km Grid)	Composite-plot (1 km x 1 km)	Sub-sampled plots (30 m x 30 m)	Unit Plots (3 m x 3 m)
Baqran Village	B	40°37'26.3"E	21°04'53.7"N	1	7	35	175
Bani Saad	CO	40°46'02.4"E	20°53'43.9"N	1	7	35	175
Al-Thumalah Farm	FTH	40°30'05.9"E	21°06'49.0"N	1	4	20	100
Jabajib	G*	40°20'31.3"E	21°20'32.5"N	1	5	25	125

Table 1 (*continued*)

Al-Hadab	HD	40°47'59.1"E	20°46'03.6"N	1	8	40	200
Wadi Muharrm	M*	40°20'09.9"E	21°21'06.2"N	1	1	5	25
Sayadah	SA*	40°59'10.2"E	20°40'12.8"N	1	1	5	25
Al-Ahada	H*	40°17'42.9"E	21°20'35.8"N	1	2	10	50
Al-Shifa	SH	40°20'04.9"E	21°06'21.8"N	1	4	20	100
Al-Thumalah	TH	40°31'11.6"E	21°08'25.5"N	1	7	35	175
Thaqeef Canal	TT	40°55'24.9"E	20°37'10.0"N	1	8	40	200
	Total			11	54	270	1350

Plant Materials and Collection of Spectral Data

From each sampling unit (3m x 3m plot), 3-4 cladodes of *Opuntia ficus-indica* were collected and used for spectral measurements. Three-point measurements of ASD field Spec-3 were performed on the collected cladodes *of Opuntia ficus-indica* varieties (*Opuntia ficus-indica* var. *inermis* and *Opuntia ficus-indica* (L) *Mill*). Spectral reflectance measurements were collected in the laboratory by the FieldSpec3 Spectroradiometer (Analytical Spectral Devices Inc., Longmont, CO, USA) using the direct-contact probe method in a wavelength range of 350-2500 nm. Three spectra were recorded from each cladode, and then the three spectra were averaged to obtain one spectral reflectance curve

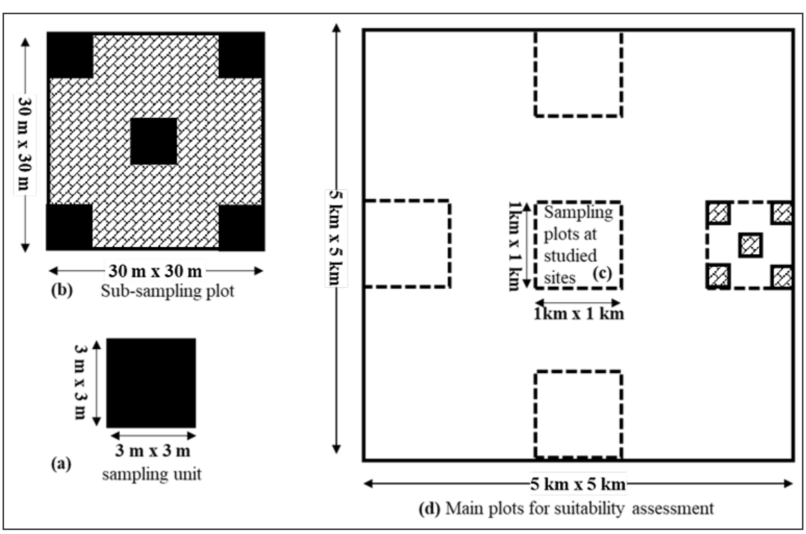

Figure 2. Sampling strategy and plot dimensions for enumeration of *Opuntia* species: (a) sampling unit; (b) sub-sampling plot; (c) sampled plot at study location/village; and (d) main plot for suitability assessment

for each plant sample. The collected spectral measurements were then used to calculate four selected vegetation indices (VIs) described in Table 2. The four VIs were adopted to monitor the growth status of cactus pear plants in different studied sites, because they can provide important insights into plants' physiological health, growth patterns, and responses to biotic and abiotic stresses.

Land Suitability Assessment (LSA)

The land suitability assessment (LSA) for the growth of two Opuntia ficus-indica varieties (*O. ficus-indica* var. *inermis* and *O. ficus-indica* (L) *Mill.*) in the southwestern region of Saudi Arabia was carried out by evaluating four selected plant indices (Table 2), which were achieved by analysing laboratory-based collected spectral measurements. The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making method widely used by many researchers for various land suitability models (Robertson & Oinam, 2023). The steps include (i) computation of vegetation indices (VIs), (ii) aggregation - mean values of computed VIs for ecological representativeness and Analytical Hierarchy Process (AHP) weights, (iii) computation of Euclidean distance for assessing spectral-ecological similarity, (iv) computation of Land suitability index (LSI) based on AHP weights (v) execution of Hierarchical Agglomerative Clustering (HAC) for ecologically homogeneous clusters, and (vi) suitability analysis of clusters based on LSI and interpretation.

The processed spectral reflectance data were used to compute key vegetation indices (NDVI, GNDVI, SAVI and NDWI), which represent vegetation greenness, chlorophyll sensitivity, soil adjusted vigour and moisture condition, respectively. ANOVA one-way (species and study sites) and two-way (species x site interaction) analysis was performed for statistical screening and identification of meaningful discrimination among studied parameters using sum of F-statistics and P-value.

Table 2
Description of vegetation indices used for this study

No.	Vegetation Index	Abbreviation	Equation	Source
1	Normalised Difference Vegetation Index	NDVI	$NDVI = \frac{NIR_{800} - Red_{670}}{NIR_{800} + Red_{670}}$	Pettorelli et al. (2005)
2	Normalised Difference Water Index	NDWI	$NDWI = \frac{NIR_{860} - SWIR_{1240}}{NIR_{860} + SWIR_{1240}}$	Gao (1996)
3	Soil Adjusted Vegetation Index	SAVI	$SAVI = \frac{1.5 \times (NIR_{800} - Red_{670})}{(NIR_{800} + Red_{670} + 0.5)}$	Huete (1988)
4	Green Normalised Difference Vegetation Index	GNDVI	$GNDVI = \frac{NIR_{810} - Green_{550}}{NIR_{810} + Green_{550}}$	Candiago et al. (2015)

The AHP analysis, described by Taherdoost (2017), was used for the derivation of weights (%) by pairwise comparison of criteria, normalisation, eigenvector extraction and reciprocal matrix. The pair-wise matrix was computed according to Eq. 1 and Eq. 2, for the studied VIs including the NDWI, NDVI, SAVI, and GNDVI to assess the LSI of *O. ficus-indica* as indirect measures of vegetation health status and water content in the plant cladode. Subsequently, priority Consistency Index (CI) and Consistency Ratio (CR) were also computed.

$$Score_i = F_{species} + F_{site} + F_{interaction} \quad [1]$$

$$Pairwwise\ matrix\ a_{ij} = textScore_i / textScore_j \quad [2]$$

where $score_i$ is the Normalised contribution of the *i-th* index.

Consequently, the LSI was computed from VIs using AHP weights, as per Eq. 3.

$$LSI = w_1 NDVI + w_2 GNDVI + w_3 SAVI + w_4 NDWI \quad [3]$$

Where *w* is the relative importance of a vegetation index; W_i is the AHP weight corresponding to VIs. The obtained LSI ranges are categorised into statistically derived four suitability classes: best (0.75 - 1.00), good (0.50-0.75), fair (0.25-0.50) and not suitable (0.00-0.25).

To identify natural ecological groupings among studied sites and Opuntia varieties (i.e., *Inermis* and *Mill*), HAC was applied using Ward's linkage and Euclidean distance on mean vegetation index values (NDVI, GNDVI, SAVI, and NDWI). The output of the hierarchical structure was visualised as dendrograms (Robertson & Oinam, 2023). Finally, the obtained cluster patterns were interpreted for land suitability with the help of LSI and elevation data across the studied locations and Opuntia varieties (i.e., *Inermis* and *Mill*). The clustering quality was assessed by employing the Silhouette Coefficient and the Davies-Bouldin Index, how well sites are species-grouped into meaningful clusters.

RESULTS AND DISCUSSION

Descriptive Statistics of the Studied Vegetation Indices

The results of vegetation indices for the two studied cactus pear varieties at different experimental sites in the southwestern region of Saudi Arabia are shown in Table 3. These results were analysed for site and variety, and significant differences were found. For example, the *inermis* variety at the TT site showed the highest values of NDWI (0.477), NDVI (0.553), and GNDVI (0.392), and the second highest value of SAVI (0.392), compared to the other study sites. While the moderate growth performance of the *Mill* variety was observed at the CO site compared to the other study sites, as shown by the highest values of NDVI (0.575), SAVI (0.428), and GNDVI (0.408). Conversely, the HD site showed the lowest values of VIs, indicating poorer vegetation conditions, with var. *inermis* having the lowest values of NDVI (0.394) and SAVI (0.301); and var. *Mill* has the lowest values of SAVI (0.260) and GNDVI (0.180).

To study the distributional characteristics of the combined VIs observations for the two cactus pear varieties at the study sites, additional descriptive statistics were performed by constructing box plots. The box plots, shown in Figure 3, demonstrated that the TT site consistently exhibited higher median values for the studied VIs, indicating better vegetation health in this region. Specifically, at the TT site, the medians of the NDWI, NDVI, SAVI and GNDVI for var. *inermis* were 0.452, 0.536, 0.377, and 0.378, respectively.

Table 3
Descriptive statistics (mean and standard deviation - SD) of vegetation indices

Variety	**Location**	**NDWI**		**NDVI**		**SAVI**		**GNDVI**	
		Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
var. *inermis*	B	0.419	0.054	0.399	0.086	0.314	0.059	0.232	0.093
	CO	0.379	0.037	0.465	0.097	0.366	0.073	0.243	0.097
	FTH	0.430	0.027	0.423	0.073	0.334	0.042	0.232	0.097
	G	0.402	0.029	0.407	0.034	0.308	0.027	0.207	0.041
	H	0.445	0.027	0.515	0.039	0.368	0.025	0.334	0.037
	HD	0.433	0.038	0.394	0.083	0.301	0.051	0.242	0.090
	M	0.428	0.020	0.565	0.055	0.406	0.051	0.364	0.061
	SA	0.453	0.023	0.526	0.016	0.365	0.013	0.372	0.022
	SH	0.448	0.032	0.528	0.051	0.374	0.027	0.378	0.041
	TH	0.417	0.032	0.443	0.057	0.343	0.042	0.270	0.065
	TT	0.477	0.053	0.553	0.065	0.392	0.031	0.392	0.064
var. *Mill*	B	0.437	0.035	0.395	0.046	0.299	0.032	0.226	0.039
	CO	0.371	0.007	0.575	0.006	0.428	0.088	0.406	0.007
	FTH	0.470	0.024	0.523	0.027	0.373	0.011	0.302	0.051
	HD	0.399	0.037	0.306	0.080	0.260	0.051	0.180	0.065
	SH	0.454	0.019	0.494	0.033	0.352	0.019	0.353	0.036
	TH	0.407	0.046	0.453	0,065	0.326	0.045	0.288	0.073
	TT	0.426	0.034	0.504	0.036	0.368	0.021	0.367	0.036

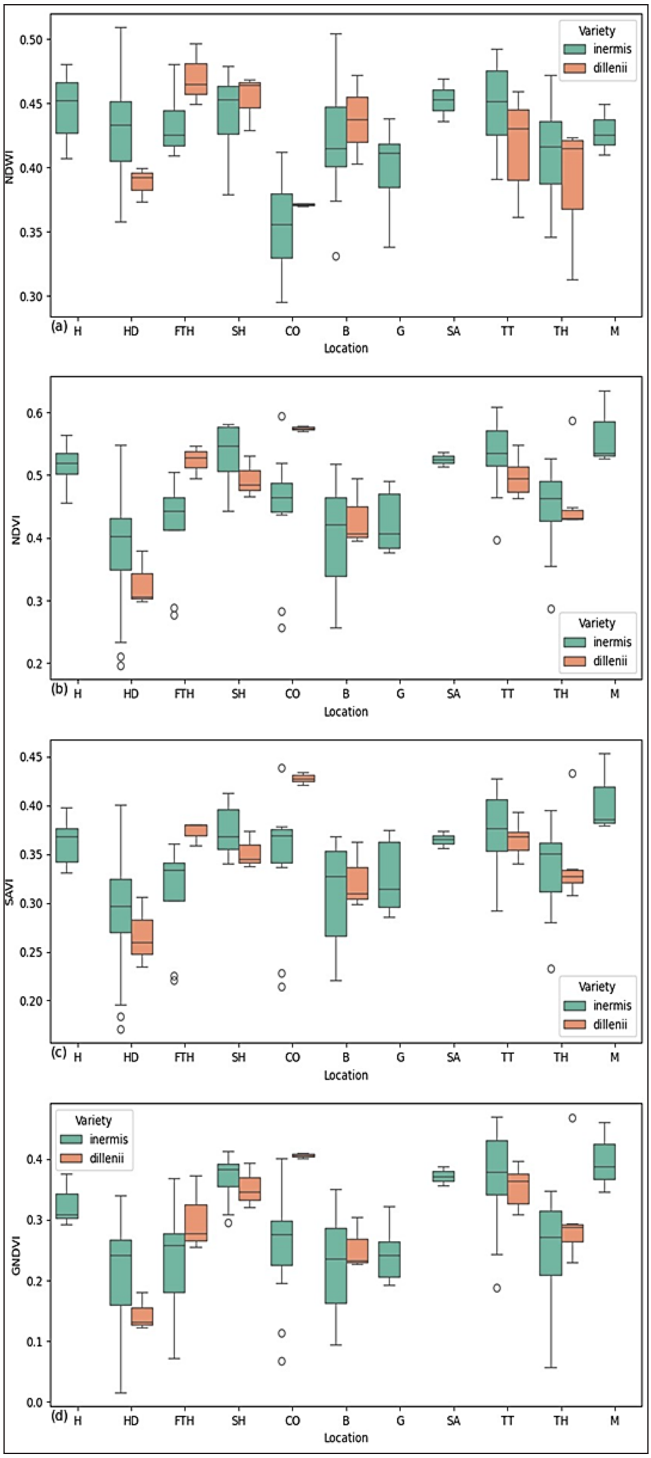

Figure 3. Box plots of the studied vegetation indices on *Opuntia* species: *O. ficus-indica* var. *inermis* and *O. ficus-indica* (L) var *Mill*

While for var. *Mill*, the medians of the NDWI, NDVI, SAVI and GNDVI at the TT site were 0.431, 0.495, 0.369, and 0.363, respectively. Conversely, the HD site showed the lowest median values, indicating poor vegetation conditions, with var. *inermis* having medians NDWI, NDVI, SAVI and GNDVI of 0.433, 0.403, 0.297, and 0.242, respectively. Meanwhile, the medians of NDWI, NDVI, SAVI and GNDVI at the HD site were 0.392, 0.306, 0.260, and 0.131, respectively.

On average, var. *inermis* outperformed var. *Mill* by recording higher medians of VIs across most study sites, highlighting its robustness and adaptability. In contrast, var. *Mill* recorded lower medians of VIs across the study sites, indicating poor vegetation health. These results underscore the importance of site and variety in influencing vegetation indices, providing valuable insights for improving agricultural practices and developing crop management strategies. Therefore, further analysis focusing on site- and variety-based interactions is necessary.

ANOVA Analysis

The ANOVA analysis showed a stronger statistical effect for NDVI, SAVI, and GNDVI (Table 4). The p-value was below 0.05 (e.g., NDVI site effect $p = 0.0165$ and GNDVI species effect $p = 0.0434$), which evidenced a significant effect, whereas higher p-values (such as NDWI species effect $p = 0.3634$) suggest no meaningful difference. The ANOVA also determined that the GNDVI ($p=0.0434$) is a significant factor for Opuntia verities. Whereas NDVI, SAVI and GNDVI were found to be significant at the site-level (p values <0.05). Moreover, with respect to species × site combinations, all the studied vegetation indices are significant. ANOVA primarily explained the ecological sensitivity of each studied VIs by measuring how strongly it varies across variety, studied locations, and their interactions. VIs with high F-values and low p-values—such as NDVI, SAVI, and especially GNDVI can be interpreted as stronger discriminatory and greater responsiveness factors.

Table 4
ANOVA results

Index	Variety Effect (F)	Species (p)	Site Effect (F)	Site (p)	Species × Site (F)	Species × Site (p)
NDWI	0.8312	0.3634	1.0671	0.3877	14.9831	<0.001
NDVI	3.2955	0.0715	2.5548	0.0165	5.4369	0.0004
SAVI	2.8689	0.0924	2.0771	0.0496	4.7616	0.0012
GNDVI	4.1494	0.0434	2.4187	0.0226	3.3555	0.0117

Land Suitability - Analytic Hierarchy Process (AHP)

The data-driven pairwise comparison matrix (Table 5) was produced to quantify the relative importance of decision criteria and represented as core input for deriving weights. The pairwise comparison matrix results reveal that GNDVI and NDVI exert the strongest influence on land suitability, followed by SAVI, while NDWI contributes comparatively less. This hierarchy reflects the dominant role of chlorophyll content and vegetation greenness in determining suitability across sites and species.

Furthermore, the eigenvector analysis found that the GNDVI scored the highest weight (0.324) followed by NDVI (0.297), SAVI (0.268) and NDWI (0.115). The final ecological weights for NDWI, NDVI, SAVI and GNDVI were 11.48%, 29.70%, 26.73 and 32.09%, respectively. The validity of weightage (%) was assessed with respect to the obtained CI (2.96×10^{-16}) and CR (3.29×10^{-16}), proven to be internally coherent (CR<0.10). The consistency ratio confirmed the logical reliability of the matrix, supporting the use of derived AHP weights in LSI computation. Among the studied VIs, the GNDVI scored the highest weight (32.09%), reflecting its strong ecological responsiveness to species, site, and interaction effects, while NDVI (29.70%) and SAVI (26.73%) were also influential, representing vegetation greenness and soil-adjusted vigour, respectively. Nevertheless, NDWI was reported with the lowest weight (11.48%), consistent with its low discrimination as detected through ANOVA results.

Table 5
AHP-derived Pairwise Matrix (A) and weights

Criteria	NDVI	GNDVI	SAVI	NDWI	Row Mean (weight)
NDVI	0.296	0.299	0.298	0.296	0.297
GNDVI	0.323	0.325	0.325	0.323	0.324
SAVI	0.266	0.27	0.269	0.266	0.268
NDWI	0.115	0.114	0.116	0.115	0.115

Table 6
AHP derived threshold values for the studied vegetation indices

Vegetation Index	*Inermis*			*Mill*		
	High	Moderate	Fair	High	Moderate	Fair
NDVI	≥ 0.52	0.45 - 0.52	< 0.45	≥ 0.49	0.42 - 0.49	< 0.42
GNDVI	≥ 0.36	0.25 - 0.36	< 0.25	≥ 0.34	0.22 - 0.34	< 0.22
SAVI	≥ 0.37	0.32 - 0.37	< 0.32	≥ 0.35	0.31 - 0.35	< 0.31
NDWI	≥ 0.44	0.40 - 0.44	< 0.40	≥ 0.43	0.41 - 0.43	< 0.41

Higher NDVI and GNDVI threshold values of *inermis* exhibited the best suitability, it explains the performance across a wider index range and establishes greater ecological adaptability. In contrast, the variety of *Mill* shows narrower threshold limits, particularly for GNDVI, higher sensitivity to chlorophyll and site conditions. On the other hand, the obtained threshold values are in agreement with the earlier reported values >0.45, >0.35, >0.35 and >0.40 for NDVI, GNDVI, SAVI and NDWI, respectively (Al-Bakre, 2025; Alexandre et al., 2025).

The land suitability index (LSI) values ranged from 0 to 1, reflecting the combined ecological contribution of each vegetation index using the final AHP weights. These LSI values were subsequently classified into four suitability categories: High (≥0.75), Moderate (0.50-0.75), Fair (0.25-0.50), and Not Suitable (<0.25). Most observations fell within the Moderate class, followed by Fair and Good, indicating that the majority of surveyed locations exhibit intermediate vegetation health influenced by site conditions and species performance. Areas classified as "Highly suitable" correspond to high NDVI and GNDVI values, reflecting vigorous vegetation, while "Fair" and Not Suitable zones were associated with lower values of spectral indices and potential ecological stress. Overall, the LSI results provide a robust, ecologically grounded assessment of land suitability, integrating multiple vegetation indices into a single, interpretable metric for decision-making and spatial planning.

The Hierarchical dendrogram visualisation and heatmaps of *O. ficus-indica L. f. inermis* (Web) and *O. ficus-indica L.* (Mill) are provided in Figures 4 and 5, respectively. To facilitate the study and discussion of the results, the groups were identified by different colours. The results of the AHP analysis were divided into three distinct groups for the cultivation of *Optunia* Species in the southwestern region of Saudi Arabia: the first group represents the highly suitable sites (green), the second group represents the moderately suitable sites (blue), and the third group represents the relatively suitable sites (red).

The heatmaps and dendrogram provide a visual representation of the hierarchical clusters of *O. ficus-indica* varieties and studied sites, based on the similarities in observed VIs (NDWI, NDVI, SAVI and GNDVI), revealing natural ecological groupings without using suitability weights. The distance between branches indicates the similarity between study sites, where closer locations have relatively similar values of VIs (Figure 4a, Figure 5-a). On the other hand, the heatmaps (Figure 4-b, Figure 5-b) depict the pairwise relationship between VIs in the different study sites for the studied *O. ficus-indica* varieties. The colours of heatmaps indicate the strength of the correlations of VIs, with red representing positive correlations and blue representing negative correlations.

As shown in Figure 4, a detailed analysis of the VIs at different sites for *O. ficus-indica* var. inermis was classified into three clusters. The study sites TT, SH, SA, H, and M were classified as "highly suitable" (green) for *O. ficus-indica* var. inermis production.

While the sites FTH, B, and HD were classified as “moderately suitable” (blue), and the sites TH, G, and CO were classified as “fairly suitable” (red). The inter-cluster linkage distances were set based on the Euclidean distance at 0.2126 (highly suitable to moderately suitable), 0.0698 (moderately suitable to fairly suitable), and 0.1661 (highly suitable to fairly suitable), and the VIs (Figure 4b) facilitate the identification of patterns and relationships between the groups.

In the case of *O. ficus-indica L. Mill,* the dendrogram (Figure 5a) shows the hierarchical clustering of sites based on the NDWI, NDVI, SAVI, and GNDVI. Three clusters were classified as "highly suitable" (green), "moderately suitable" (blue), and "fairly suitable" (red) sites for the growth. The linkage distances between clusters are 0.0388 (highly suitable to moderately suitable), 0.0763 (moderately suitable to fairly suitable), and 0.0794 (highly suitable to fairly suitable). While the heat map (Figure 5b) illustrates the magnitude of the vegetation indices for each site. The colour intensity represents the magnitude of the values, with a colour scale ranging from cool (low values) to warm (high values).

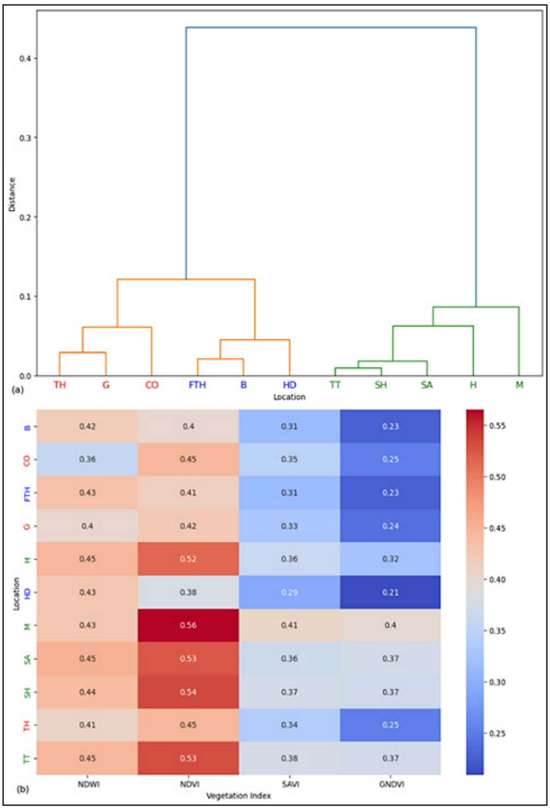

Figure 4. (a) Hierarchical dendrogram classification (AHP); and (b) Heatmap of the studied VIs at different sites for the cultivation of *O. ficus-indica L.* var. *inermis* (web). The sites in the X-axis are marked by green, blue, and red colours, which represent highly suitable, moderately suitable, and fairly suitable, respectively

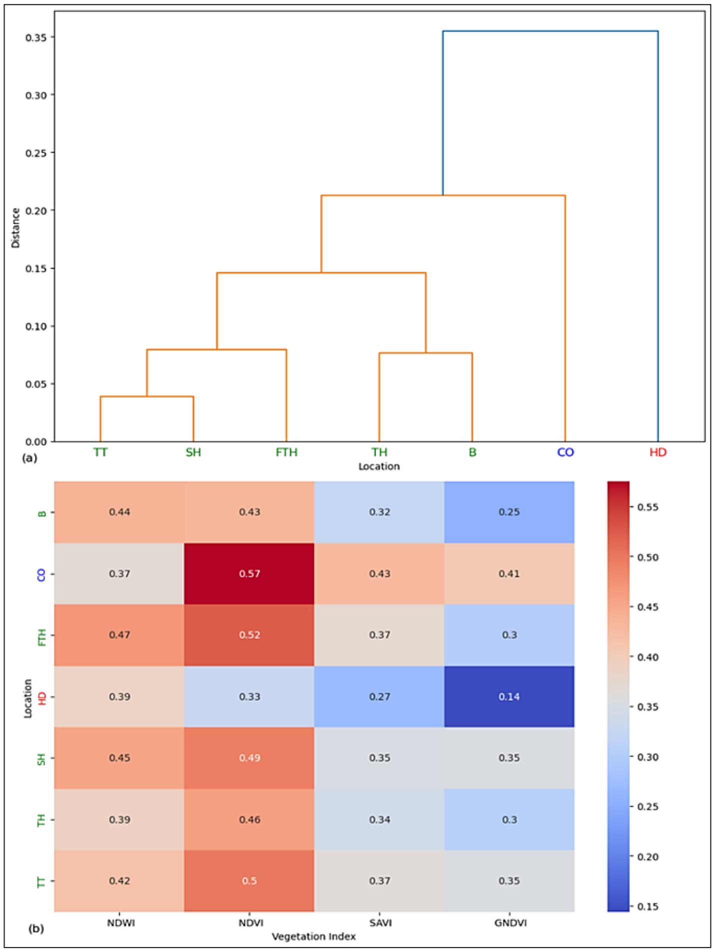

Figure 5. (a) Hierarchical dendrogram classification (AHP); and (b) Heatmap of the studied VIs at different sites for the cultivation of *O. ficus-indica L.* (*Mill*). The sites in the X-axis are marked by green, blue, and red colours, which represent highly suitable, moderately suitable, and fairly suitable, respectively

The mean values of the indices are NDWI (0.418), NDVI (0.473), SAVI (0.350), and GNDVI (0.302). The standard deviations are NDWI (0.037), NDVI (0.078), SAVI (0.049), and GNDVI (0.085), indicating the variability of the indices across sites, facilitating the identification of patterns and relationships within the data. The "highly suitable" group includes sites B, FTH, SH, TH, and TT; the "moderately suitable" group includes site CO; and the "fairly suitable" group includes site HD.

Moreover, the LSI overlaid clusters revealed clear site-dependent suitability patterns for both *inermis* and *Mill* varieties (Table 7). For *inermis*, sites M, SA, SH, and TT were found to be "highly suitable" locations with the highest LSI values (0.70-0.81).

Moderately suitable conditions (0.50-0.70) were observed in sites CO, FTH, G, HD, H, and TH. Whereas, for the variety *mill*, highly suitable sites were TT, SH, and CO, with LSI values ranging between 0.58-0.74, while sites such as TH, FTH, and B showed moderate suitability (0.50-0.60). The least suitable site for the *Mill* was HD (LSI = 0.347), indicating ecological constraints affecting its performance. These site Code-based suitability patterns align with the AHP weighting scheme and clustering patterns, confirming strong ecological differentiation across sites.

Across the study area, land suitability assessment provided a distinct representation with respect to the studied *O. ficus-indica* varieties (*inermis* and *Mill*) and site-dependent response to location. Study sites located within the mid-to-high elevation range (~1700-2100m a.s.l.) corresponded with "high suitable sites". Consequently, the elevation alone has no role in suitability performance. *Inermis* found to have broader elevation adaptability and high suitability across both moderate and higher elevations (~1669-2047 m), has proven its greater ecological resistance. However, *O. ficus-indica* var. *Mill* was shown to have highly suitable sites ranging between ~1850m and 2100m elevation ranges. In contrast, study sites with similar elevation ranges often differed in suitability class, confirming that the local site conditions and *O. ficus-indica* varieties and AHP-weighted VIs played a major role in suitability class determination, but not the elevation factor alone. On the other hand, elevation is represented as an influencing ecological component, but not as a controlling factor on *O. ficus-indica* varieties and land suitability across study sites.

Table 7

Land suitability for the growth of O. ficus-indica *based on LSI and clustering analysis*

Site Code	Study Site	Elevation (m a.s.l.)	*Mill*		*Inermis*	
			LSI	Suitability	LSI	Suitability
B	Baqran Village	1749	0.503	Moderate	0.490	Fair
CO	Bani Saad	2278	0.579	High	0.576	Moderate
FTH	Al-Thumalah Farm	1729	0.513	Moderate	0.599	Moderate
G	Jabajib	1823	-	-	0.519	Moderate
HD	Al-Hadab	2105	0.347	Fair	0.516	Moderate
M	Wadi Muharrm	1980	-	-	0.814	High
SA	Sayadah	1669	-	-	0.744	High
H	Al-Ahada	2073	-	-	0.697	Moderate
SH	Al-Shifa	2074	0.68	High	0.780	High
TH	Al-Thumalah	1687	0.555	Moderate	0.575	Moderate
TT	Thaqeef Canal	1856	0.739	High	0.741	High

Accuracy Assessment

The Silhouette Coefficient and Davies-Bouldin Index (DBI) are widely used cluster validity measures that assess how well sites and species-grouped ecological conditions separate into meaningful clusters. In this study, hierarchical clustering (Ward's method) was applied both site-wise and species × site-wise, producing compact, interpretable groupings of vegetation performance based on GNDVI, NDVI, SAVI, and NDWI responses. The site-wise clustering showed a strong Silhouette score (0.5258) and a low DBI (0.3571), indicating well-separated and compact clusters among study sites, which differ in vegetation structure and ecological condition with high clarity. In contrast, the species × site clustering produced a moderate Silhouette value (0.3572) and higher DBI (0.5569), reflecting more overlap and weaker cluster separation, consistent with the ecological interaction between species and environmental gradients. Overall, these indices confirm that site-level ecological differences are more distinct than species × site interactions, reinforcing the validity of AHP-driven suitability patterns.

Limitations of the Study

In view of the hyper-arid conditions of the study area, where the desert vegetation, such as *Opuntia* spp., is can survive in harsh temperatures and low rainfall. This study was limited to the most influential variables at the landscape scale, i.e., physiological performance-based vegetation indices (NDWI, SAVI, GNDVI and NDVI). Land suitability was performed as described by Robertson and Oinam (2023). This systematic approach enables accurate land assessment to improve Opuntia sp. production, particularly (*O. ficus-indica* (L) *Mill*. and *O. ficus-indica* var. *inermis*), while ensuring sustainable agroforestry and horticultural practices. Moreover, *Opuntia* spp. are characterised as high water-use efficiency with stress-tolerant plants under prolonged drought conditions, hence moisture-related or red-edge spectral indices were not studied as those are low-influential parameters at the landscape scale (Louhaichi et al., 2015).

CONCLUSION

This study was conducted to investigate the growth of two *Opuntia ficus-indica* varieties (var. *inermis* and var. Mill) in eleven geographical sites located in the southwestern region of Saudi Arabia. The main objective was to identify suitable production sites using spectral vegetation indices (VIs), and to determine the most performing variety in each site. Based on the results of VIs, the Thaqeef Canal site consistently exhibited higher values compared to other sites, indicating better vegetation health in this site. However, among *Opuntia ficus-indica* varieties, the results of VIs indicated that the var. *inermis* outperformed the var. Mill by recording higher values of VIs in most study sites. Additional analysis focusing on site- and cultivar-based interactions was carried out using the Analytical Hierarchy Process (AHP). The results of the AHP indicated that Thaqeef Canal and Al-Shifa were the most suitable sites for the growth of both *Opuntia ficus-indica* varieties. Other sites considered highly suitable for growing the var *inermis* were Wadi Muharrm and Sayadah. While Baqran Village, Al-Thumalah farm, and Al-Thumalah were considered highly suitable for the growth of the var. Mill. The results of this study provide a good basis for subsequent studies aimed at improving agricultural practices and decision-making related to the production of *Opuntia ficus-indica* in the southwestern region of Saudi Arabia.

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LIST OF ABBREVIATIONS

H	Al-Ahada
HD	Al-Hadab
FTH	Al-Thumalah Farm
SH	Al-Shifa
CO	Bani Saad
B	Baqran Village
G	Jabajib
SA	Sayadah
TT	Thaqeef Canal
TH	Al-Thumalah
M	Wadi Muharrm
NDVI	Normalised Difference Vegetation Index
NDWI	Normalised Difference Water Index
SAVI	Soil Adjusted Vegetation Index
GNDVI	Green Normalised Difference Vegetation Index
LSA	Land Suitability Assessment
VIs	Vegetation Indices
AHP	Analytical Hierarchy Process
MDPI	Multidisciplinary Digital Publishing Institute
DOAJ	Directory of Open Access Journals
TLA	Three-letter Acronyms
LD	Linear Dichroism

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